

Proposed Pragmatic Methods for
Estimating Plume Rise and Plume
Penetration through Atmospheric Layers

(U.S.) Environmental Protection Agency
Research Triangle Park, NC

1985



U.S. Department of Commerce
National Technical Information Service

NTIS

TECHNICAL REPORT DATA
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1. REPORT NO. EPA/600/J-85/505		2.	3. RE PB88-139886
4. TITLE AND SUBTITLE PROPOSED PRAGMATIC METHODS FOR ESTIMATING PLUME RISE AND PLUME PENETRATION THROUGH ATMOSPHERIC LAYERS (Journal Version)		5. REPORT DATE 1985	
7. AUTHOR(S) D. Bruce Turner		6. PERFORMING ORGANIZATION CODE	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Atmospheric Sciences Research Laboratory Office of Research and Development U. S. Environmental Protection Agency Research Triangle Park, NC 27711		8. PERFORMING ORGANIZATION REPORT NO.	
12. SPONSORING AGENCY NAME AND ADDRESS Atmospheric Sciences Research Laboratory Office of Research and Development U. S. Environmental Protection Agency Research Triangle Park, NC 27711		10. PROGRAM ELEMENT NO. CDTA1D/U8-2182 (FY-84)	
		11. CONTRACT/GRANT NO.	
		13. TYPE OF REPORT AND PERIOD COVERED	
		14. SPONSORING AGENCY CODE EPA/600/U9	
15. SUPPLEMENTARY NOTES Atmospheric Environment, 19(7):1215-1218, July 1985			
16. ABSTRACT Methods are proposed for estimating plume rise taking advantage of data on the vertical variation of wind speed and temperature. In addition, partial penetration of the plume into the stable layer above the mixing height is considered.			
17. KEY WORDS AND DOCUMENT ANALYSIS			
a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
REPRODUCED BY U.S. DEPARTMENT OF COMMERCE NATIONAL TECHNICAL INFORMATION SERVICE SPRINGFIELD, VA. 22161			
18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC		19. SECURITY CLASS (This Report) UNCLASSIFIED	21. NO. OF PAGES 7
		20. SECURITY CLASS (This page) UNCLASSIFIED	22. PRICE PC9.95/MT 6.95

PRELIMINARY COMMUNICATIONS

PROPOSED PRAGMATIC METHODS FOR ESTIMATING PLUME RISE AND PLUME PENETRATION THROUGH ATMOSPHERIC LAYERS

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(First received 8 August 1984 and in final form 4 April 1985)

1. INTRODUCTION — Nearly all of the air quality simulation models made readily available through the UNAMAP system (U.S. EPA, 1983), use plume rise methodology dependent on the wind speed estimated at physical stack top and the surface based Pasquill stability class. For situations where additional meteorological information is available, such as wind speed and temperature profiles with height, it is highly desirable to use this information.

Most of the current models also treat plumes in the vicinity of the mixing height in an overly simplistic, all-or-nothing way. Methods have been suggested by Briggs (1975) and others (Weil and Brower, 1982) to consider partial penetration of the plume into the more stable layer above the mixing height. A modification of those methods is presented here.

The purpose of this communication is to outline techniques that can be used to calculate plume rise and penetration through atmospheric layers in order that those who have appropriate plume rise and meteorological data might examine these techniques critically and endorse these procedures or propose alternatives.

2. METEOROLOGICAL DATA AVAILABLE BY LAYERS — These procedures are designed to take advantage of methods developed by Briggs to consider the vertical structure of meteorological parameters in estimating plume rise. It is assumed here that temperature, and wind speed will be available at a number of levels (at least two) above the ground. It is also assumed that the mixing height and the rate of change of potential temperature with height $\delta\theta/\delta z$ above the mixing height are available. It is assumed that the meteorological information given at different levels can be sufficiently dense in the vertical so that linear interpolation of the parameters between levels yields reasonable values.

For the application of a dispersion model (such as TUPOS, of which these procedures have become a part) values for the additional parameters: wind direction, standard deviation of horizontal wind fluctuation, and standard deviation of vertical wind fluctuation are also specified at each level. When the height of the plume centerline has been determined, interpolated values of these parameters for that height are used to determine plume transport direction and Gaussian dispersion parameters.

3. PLUME RISE AND PENETRATION CALCULATIONS — The following source parameters are assumed available: Emission rate Q , physical stack height h , stack inside diameter d , stack gas temperature T_s , and stack gas exit velocity v_g . From the given meteorological information, the ambient temperature at stack top T_a and the wind speed at stack top u_h can be determined. Subscripts b and t refer to the base and top of a layer, respectively. Considering each layer, z_b and z_t are the heights of the base and top of the layer above stack top. $\delta\theta/\delta z$ can be calculated from $[(T_t - T_b)/(z_t - z_b)] + 0.0098$, $\Delta T = T_s - T_a$, g is the acceleration due to gravity (9.806).

The top portion of the flow chart uses the method of Bjorklund and Bowers (1982) to estimate f , the stack tip downwash correction factor. Fr is the Froude number. Neutral-unstable momentum rise is estimated with eq.(3) and initial buoyancy flux F_0 with eq.(4). For stacks of other than circular cross-section, replace $d^2/4$ by the cross-sectional area divided by π . In estimating the initial buoyancy flux, for flares, $F_0 = a (2.8 \times 10^{-5}) Q_H$ where Q_H is the heat emission in cal s^{-1} and can be calculated from the sum of the low heats of combustion of the

constituents and their volume flows. The coefficient a is a quantity to account for that portion of the heat not lost as radiant heat and can be expected to vary between 0.45 and 0.80.

Initial plume rise calculations are made using u_h for u and T_a at stack top for T in the plume rise equations. If the plume rise (for neutral-unstable) or the plume top (for stable) exceeds the top of the layer containing the stack top, computations are repeated using the mean wind and temperature between stack top and the top of the layer. For other layer calculations, mean wind and temperature are used for each layer.

The left side of the flow chart estimates the plume rise ΔH (stack top to plume center-line) for neutral-unstable conditions; eqs.(5) and (6) are a modification (Briggs, 1983) to techniques presented by Briggs (1984). Eq.(5) will give the lowest values for low wind speeds; eq.(6) will give the lowest values for high wind speeds.

The right side of the flow chart estimates the plume top ΔH_t (stack top to plume top) for stable conditions; eqs.(10) and (11) are a modification to Briggs (1975). Equation (10) will give lowest values for high winds. Equation (11) is for calm or near calm conditions. Stable momentum rise; eq.(9) is also calculated and the lowest value of eq.(3) or (9) used for momentum rise to compare with the buoyancy rise.

When rise (or plume top for stable) exceeds the top of the layer, the residual buoyancy of the plume at the top of the layer F_R is calculated and used to calculate the rise in the next layer.

The bottom part of the flow chart considers penetration. The emission rate Q' , the plume height H' , and the plume rise $\Delta H'$ are modified according to the flow chart. A "top hat" (uniform concentrations through a depth) plume with the plume thickness equal to the rise is assumed.

4. DISTANCE TO FINAL RISE — Except for the situation of the plume rise being due to momentum, in which case the distance to final rise is taken to be zero, the plume is assumed to rise to its final height using the 2/3 rule (Briggs, 1971, p. 1030): $\Delta H(x) = 160 F^{1/3} x^{2/3}/u$ (14), where x is the downwind distance from the source in km. Although it should be possible to calculate the distance traveled to achieve the rise through each layer, that degree of sophistication seems unnecessary and for any of the buoyant rise situations the distance to final rise is calculated from: $x_f = [u_h \Delta H' / (160 F_o^{1/3})]^{1.5}$ (15).

5. TWO EXAMPLES — The point source used for the examples has the following characteristics: physical stack height $h = 200$ m, stack top inside diameter $d = 6.9$ m, stack gas temperature $T_g = 450$ K, stack gas exit velocity $v_g = 20.$, and the pollutant emission rate $Q = 1000$.

Example 1 (See Table) represents a situation with unstable conditions near the ground with an elevated inversion (such as mid-morning on a clear day). $Fr = 11.3$. Since $v_g > 1.5 u_h$, $f = 1$. The physical stack height is within layer 4. Layers are numbered according to the level number of its bottom. Temperature and wind speed at stack height are $T_h = 295.8$, $u_h = 3.7$. The initial buoyancy flux F_o is 799.9. Mixing height is 500 m and the results are given in the right side of the Table and following. Plume rise and plume height are $\Delta H = 2/3 \Delta H_t = 202.5$, $H = 402.5$. Penetration is considered. The following are determined: plume top = 503.7, plume bottom = 301.2, $H' = 400.6$, $Q' = 982$, and $\Delta H' = 200.6$, $x_f = 0.353$ km.

Example 2 (See Table) represents a situation with a ground-level inversion that extends to 300 m with neutral-unstable conditions above (perhaps early evening or nighttime). The mixing height is undefined. The physical stack height is within layer 4. The initial buoyancy flux F_o is 791.1. The results are given in the right side of the Table and following. $\Delta H = 173.4$, $H = 373.4$ and H' , Q' , and H' are the same as the unprimed quantities. The distance to final rise $x_f = 1.345$ km.

6. SUMMARY — Practical techniques have been presented for estimating plume rise through layers of the atmosphere characterized by wind speed and temperature at a number of levels above ground and how to consider the plume penetration into an elevated stable layer above the mixing height.

ACKNOWLEDGEMENT -- The author gratefully acknowledges the discussion and comments of Gary A. Briggs and the secretarial assistance of Patrick Langston and Sylvia Alston.

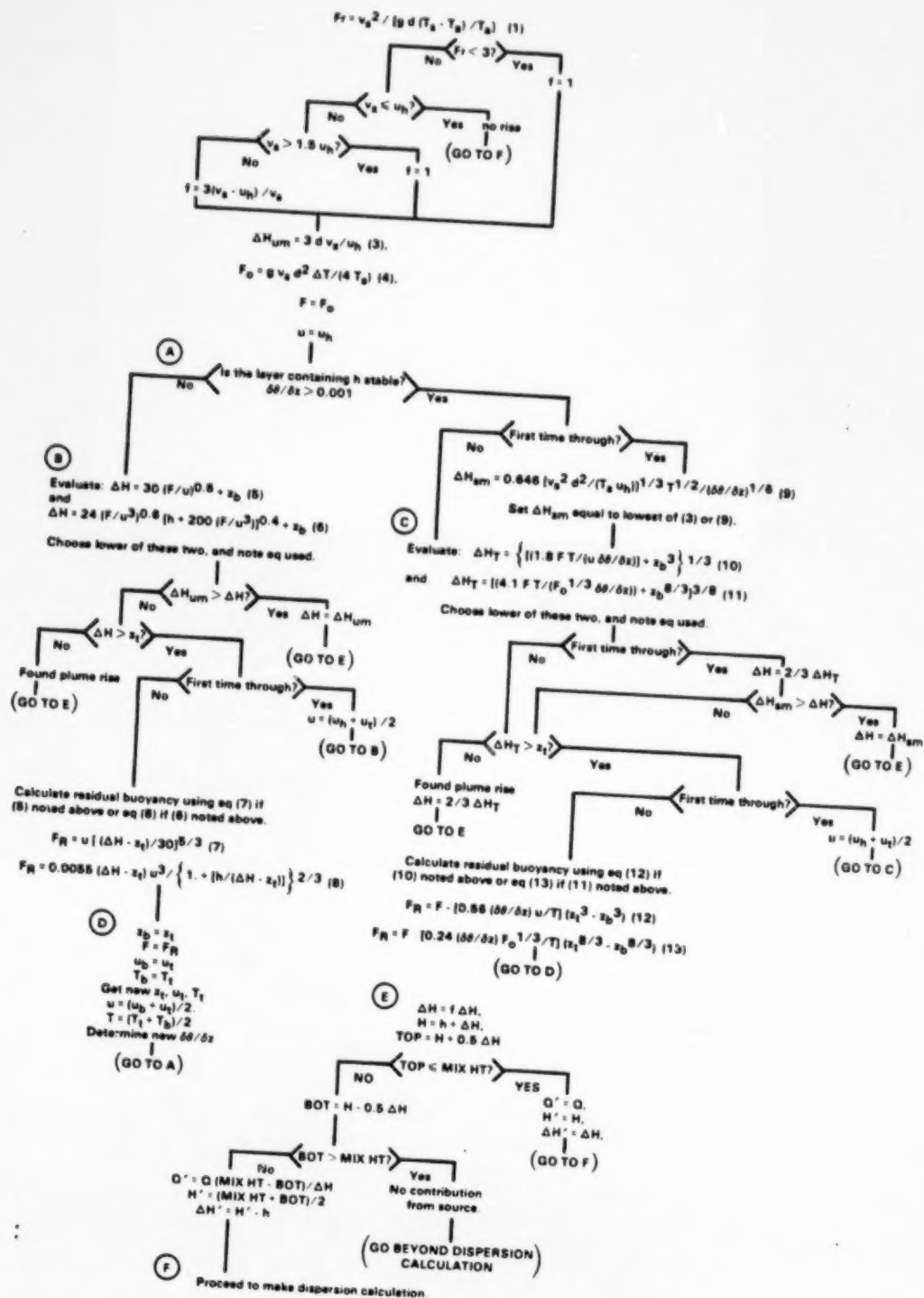
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TABLE. METEOROLOGICAL CONDITIONS AND RESULTS FOR THE TWO EXAMPLES.

LEVEL NO.	HEIGHT ABOVE GROUND	T ° K	$\delta\theta/\delta z$ ° m ⁻¹	MEAN T ° K	U m s ⁻¹	MEAN HEIGHT ABOVE STACK TOP m	
INPUT -- EXAMPLE 1.							
1	2	298.			1.0	-198	
			-0.0152	297.9		2.0	
2	10	297.8			3.0	-190	
			-0.0013	297.3		3.25	
3	100	296.8			3.5	-100	AT STACK
			-0.0002	296.3		3.6	HEIGHT $\Delta H_{um}=111.9$, $\Delta H(5)=755.1$, $\Delta H(6)=3233.8$
4	200	295.8			3.7	0	
			-0.0002	295.3		3.75	LAYER 4. $\Delta H(5)=749.1$, $\Delta H(6)=3109.2$, $F_R=630.0$
5	300	294.8			3.8	100	
			0.0008	294.35		3.85	LAYER 5. $\Delta H(5)=738.9$, $\Delta H(6)=2383.6$, $F_R=474.4$
6	400	293.9			3.9	200	
			0.0008	293.45		3.9	LAYER 6. $\Delta H(5)=734.8$, $\Delta H(6)=1875.0$, $F_R=335.9$
7	500	293.			3.9	300	
			0.0398	294.5		4.45	LAYER 7. $\Delta H_T(10)=303.7$, $\Delta H_T(11)=328.3$
8	600	296.			5.0	400	
INPUT -- EXAMPLE 2.							
1	2	293.			1.0	-198	
			0.0473	293.15		1.5	
2	10	293.3			2.0	-190	
			0.0398	294.8		4.55	
3	100	296.			7.1	-100	AT STACK
			0.0248	296.75		8.75	HEIGHT $\Delta H_{um}=39.808$, $\Delta H_{sm}=35.9$
4	200	297.5			10.4	0	HEIGHT $\Delta H_T(10)=140.1$, $\Delta H_T(11)=369.9$
			0.0148	297.75		11.7	LAYER 4. $\Delta H_T(10)=134.7$, $\Delta H_T(11)=369.9$, $F_R=465.1$
5	300	298.			13.0	100	
			0.0008	297.55		14.0	LAYER 5. $\Delta H(5)=345.5$, $\Delta H(6)=173.3$
6	400	297.1			15.0	200	

DETERMINING PLUME RISE - FLOW CHART



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